IRRIGATION SYSTEM EFFICIENCIES[1]

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INTRODUCTION

"Irrigation efficiency" is a basic engineering term used in irrigation science to characterize irrigation performance, evaluate irrigation water use, and to promote better or improved use of water resources, particularly those used in agriculture (Israelsen and Hansen, 1962; ASCE, 1978; Bos, 1979; and Heermann et al., 1990). Irrigation efficiency is a critical measure of irrigation performance in terms of the water needed to irrigate a field, farm, basin, irrigation district, or an entire watershed. Irrigation efficiency is defined in terms of

- irrigation system performance
- uniformity of the water application
- response of the crop to irrigation

Each of these irrigation efficiency measures is interrelated and will vary with scale and time. Figure 1 illustrates several of the water transport components involved in defining various irrigation performance measures. The spatial scale can vary from a single irrigation application device (a siphon tube, a gated pipe gate, a sprinkler, a microirrigation emitter) to an irrigation set (a basin plot or set, a furrow set, a single sprinkler lateral, a microirrigation lateral) to broader land scales (field, farm, an irrigation canal lateral, a whole irrigation district, a basin or watershed, or a river system, or an aquifer). The time scale can vary from a

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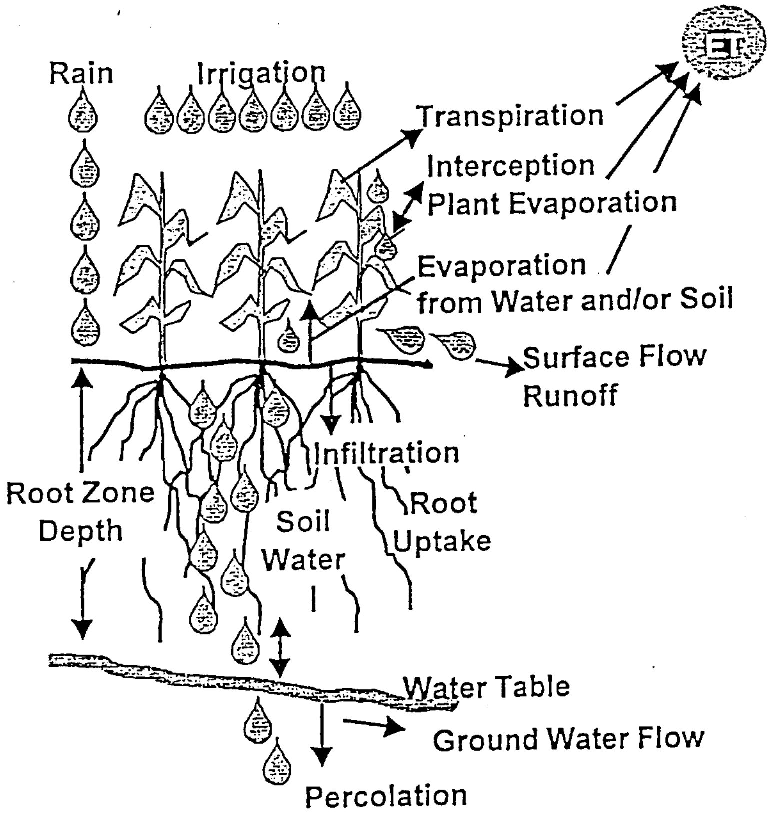

Figure 1. Illustration of various water transport components needed to characterize irrigation efficiency.

single application (or irrigation set), a part of the crop season (preplanting, emergence to bloom or pollination, reproduction to maturity), the irrigation season, to a crop season, or a year, partial year (pre-monsoon season, summer, etc.), or a water year (typically from the beginning of spring snow melt through the end of irrigation diversion, or a rainy or monsoon season), or a period of years (a drought or a "wet" cycle). Irrigation efficiency affects the economics of irrigation, the amount of water needed to irrigate a specific land area, the spatial uniformity of the crop and its yield, and the amount of water that might percolate beneath the crop root zone. It can also affect the amount of water that can return to surface sources for downstream uses or to ground water aquifers that might supply other water uses, and the amount of water lost to unrecoverable sources (salt sinks, saline aquifer, or an unsaturated vadose zone).

The volumes of the water for the various irrigation components are typically expressed in units of depth (volume per unit area) or simply the volume for the area being evaluated. Irrigation water application volume is difficult to measure; so, it is usually computed as the product of water flow rate and time. This places emphasis on accurately measuring the flow rate. The accurate measurement of water percolation volumes, ground water flow volumes, and water uptake from shallow ground water remain difficult under most circumstances.

IRRIGATION SYSTEM PERFORMANCE EFFICIENCY

Irrigation water can be diverted from a storage reservoir and transported to the field or farm through a system of canals or pipelines; it can be pumped from a reservoir on the farm and transported through a system of farm canals or pipelines; or it might be pumped from a single well or a series off wells through farm canals or pipelines. Irrigation districts often include small to moderate size reservoirs to regulate flow and to provide short-term storage to manage the diverted water with the on-farm demand. Some on-farm systems include reservoirs for storage or regulation of flows from multiple wells. This latter case is often used with longer center pivots (half-mile ones) with a centrifugal pump to boost the water to the desired elevation or pressure for the pivot.

Water Conveyance Efficiency

The conveyance efficiency is typically defined as the ratio between the water that reaches a farm or field to that diverted from the irrigation water source (Israelsen and Hansen, 1962; Bos, 1979; and Heermann et al., 1990). It is defined as

$$E_c = 100\frac{V_f}{V_t} \qquad \text{...[1]}$$

where E_c is the conveyance efficiency in percent, V_f is the volume of water that reaches the farm or field (m^3 or gallons[1]), and V_t is the volume of water diverted (m^3) from the source. E_c also applies to segments of canals or pipelines, where the water losses include canal seepage or leaks in pipelines. The global E_c can be computed as the product of the individual component efficiencies, E_{ci}, where i represents the segment number. Conveyance losses include any canal spills (operational or accidental) and reservoir seepage and evaporation that might result from management as well as losses resulting from the physical configuration or condition of the irrigation system. Typically, conveyance losses are much lower for closed conduits or pipelines (Heermann et al., 1990) compared with unlined or lined canals. Even the conveyance efficiency of lined canals may decline over time due to material deterioration or poor maintenance. Limited data exists to document pipeline seepage from older under ground concrete pipelines contrasted with newer PVC pipelines in the Great Plains.

[1] The volumetric units used are less important (metric or English), but they need to be consistently applied. Water volume could be in ac-ft or ac-in. or gallons or ft^3.

Application Efficiency

Application efficiency relates to the actual storage of water in the root zone to meet the crop water needs in relation to the water applied to the field. It might be defined for individual irrigations or parts of irrigations (irrigation sets). Application efficiency includes any application losses to evaporation or seepage from surface water channels or furrows, any leaks from sprinkler or drip pipelines, percolation beneath the root zone, drift from sprinklers, evaporation of droplets in the air, or runoff from the field. Application efficiency is defined as

$$E_a = 100 \frac{V_s}{V_f} \qquad \text{...[2]}$$

where E_a is the application efficiency in percent, V_s is the irrigation needed by the crop (m^3), and V_f is the water delivered to the field or farm (m^3). The root zone may not need to be fully refilled with each irrigation, particularly if some root zone water holding capacity is needed to store possible or likely rainfall. Often, V_s is characterized as the volume of water stored in the root zone from the irrigation application. Some irrigations may be applied for reasons other than meeting the crop water requirement (germination, frost control, crop cooling, chemigation, fertigation, weed germination). The crop need is often based on the "beneficial water needs" (Burt et al. 1997). In some surface irrigation systems, the runoff water that is necessary to achieve good uniformity across the field can be recovered in a "tailwater pit" and recirculated with the current irrigation or used for later irrigations, and V_f should be adjusted to account for the "net" recovered tailwater. Efficiency values are typically site specific. Table 1 provides a range of typical farm and field irrigation application efficiencies (Howell, 1988; Merriam and Keller, 1978; Keller and Bliesner, 2000) and potential or attainable efficiencies for different irrigation methods that assumes irrigations are applied to meet the crop need. E_a is not to be regarded as a "constant", because many factors can cause it to vary temporally, spatially, and even for differing irrigation methods. Too often E_a is taken as a "constant" for a particular irrigation method in comparison with another irrigation method to estimate potential water savings or irrigation costs when it is intended to be used to characterize system performance and adjust system design or management parameters to achieve improved water use.

Table 1. Example farm and field irrigation application efficiencies and attainable efficiencies (Howell, 1988; Merriam and Keller, 1978; and Keller and Bliesner, 2000).

Irrigation Method	Field Efficiency, %			Farm Efficiency, %		
	Attainable	Range	Avg.	Attainable	Range	Avg.
Surface						
Graded Furrow	75	50-80	65	70	40-70	65
w/tailwater reuse	85	60-90	75	85	--	--
Level Furrow	85	65-95	80	85	--	--
Graded Border	80	50-80	65	75	--	--
Level Basins	90	80-95	85	80	--	--
Sprinkler						
Periodic Move	80	60-85	75	80	60-90	80
Side Roll	80	60-85	75	80	60-85	80
Moving Big Gun	75	55-75	65	80	60-80	70
Center Pivot						
Impact heads w/end gun	85	75-90	80	85	75-90	80
Spray heads wo/end gun	95	75-95	90	85	75-95	90
LEPA* wo/end gun	96	80-98	92	95	80-98	90
Lateral Move						
Spray heads						
w/hose feed	95	75-95	90	85	80-98	90
Spray heads						
w/canal feed	90	70-95	85	90	75-95	85
Microirrigation						
Trickle	96	70-95	88	95	75-95	88
Subsurface Drip	96	75-95	90	95	75-95	90
Microspray	92	70-95	85	95	70-95	85
Water Table Control						
Surface Ditch	80	50-80	65	80	50-80	60
Subsurface Drain Lines	85	60-80	75	85	65-85	70

*LEPA is low energy precision application.

Storage Efficiency

Since the crop root zone may not need to be refilled with each irrigation (in this case, E_a can be nearly 100% if no percolation or runoff occurs), the storage efficiency has been defined (Heermann et al., 1990) to account for the root zone storage capacity and the crop water need. The storage efficiency is given as

$$E_s = 100 \frac{V_s}{V_{rz}} \qquad \text{...[3]}$$

where E_s is the storage efficiency in percent and V_{rz} is the root zone storage capacity (m^3). The root zone depth and the water holding capacity of the root zone determine V_{rz}. The storage efficiency has little utility for sprinkler or microirrigation, because these irrigation methods seldom refill the root zone completely, while it is more often applied to surface irrigation methods (Heermann et al., 1990) in which often the root zone soil water deficit is fully replenished. The storage efficiency and be applied to an individual irrigation event or to various parts of the irrigation season or year.

Seasonal Irrigation Efficiency

The seasonal irrigation efficiency is defined as

$$E_i = 100 \frac{V_b}{V_f} \qquad \text{...[4]}$$

where E_i is the seasonal irrigation efficiency in percent and V_b is the water volume beneficially used by the crop (m^3). V_b is somewhat subjective (Heermann et al., 1990; and Burt et al., 1997), but it basically includes the required crop evapotranspiration (ET_c) plus any required leaching water (V_l) for salinity management of the crop root zone.

Leaching Requirement (or the leaching fraction)

The leaching requirement (U.S. Salinity Laboratory Staff, 1954), also called the leaching fraction, is defined as

$$L_r = \frac{V_d}{V_f} = \frac{EC_i}{EC_d} \qquad \ldots[5]$$

where L_r is the leaching requirement, V_d is the volume of drainage water (m^3), V_f is the volume of irrigation (m^3) applied to the farm or field, EC_i is the electrical conductivity of the irrigation water (dS m^{-1}), and EC_d is the electrical conductivity of the drainage water (dS m^{-1}). The L_r is related to the irrigation application efficiency, particularly when drainage is the primary irrigation loss component. The L_r would be required "beneficial" irrigation use ($V_l \equiv L_r V_i$) where V_i is beneficial irrigation (m^3), so only V_d greater than the minimum required leaching should reduce irrigation efficiency. Then, the irrigation efficiency can be determined by combining equations [4] and [5]

$$E_i = 100\left(\frac{V_b}{V_f} + L_r\right) \qquad \ldots[6]$$

Burt et al. (1997) defined "beneficial" water use to include possible off-site needs to benefit society (riparian needs or wildlife or fishery needs). They also indicated that V_f should not include the change in the field or farm storage of water but it could include field (tailwater pits) or farm water storage (a reservoir) that wasn't used within the time frame that was used to define E_i.

IRRIGATION UNIFORMITY

The fraction of water used efficiently and beneficially is important to improved irrigation practice. The uniformity of the applied water significantly affects irrigation efficiency. This uniformity is a statistical property of the applied water's distribution. This distribution depends on many factors that are related to the method of irrigation, soil topography, soil hydraulic or infiltration characteristics, and hydraulic characteristics (pressure, flow rate) of the irrigation system. Irrigation application distributions are usually based on depths of water (volume per unit area); however, for microirrigation systems they are usually based on emitter flow volumes because the entire land area is not typically wetted.

Christiansen's Uniformity Coefficient

Christiansen (1942) proposed a coefficient intended mainly for sprinkler systems based on the catch volumes given as

$$C_U = 100\left[\frac{1-\left(\sum |X-\bar{x}|\right)}{\sum X}\right] \qquad \text{...[7]}$$

where C_U is the Christiansen's uniformity coefficient in percent, X is the depth (or volume) of water in each of the equally spaced catch containers in mm or ml, and $\bar{x}$ is the mean depth (volume) of the catch (mm or ml). For C_U values > 70%, Hart (1961) and Keller and Bliesner (2000) presented

$$C_U = 100\left[1-\left(\frac{\sigma}{\bar{x}}\right)\left(\frac{2}{\pi}\right)^{0.5}\right] \qquad \text{...[8]}$$

where σ is the standard deviation of the catch depth (mm) or volume (ml). Equation [8] approximates the normal distribution for the catch amounts.

The C_U should be weighted by the area represented by the container (Heermann and Hein, 1968) when the sprinkler catch containers intentionally represent unequal land areas, as is the case for catch containers beneath a center pivot. Heermann and Hein (1968) revised the C_U formula (equation [8]) to reflect the weighted area, particularly intended for a center pivot sprinkler, as follows:

$$C_{U(H\&H)} = 100\left\{1-\left[\frac{\left(\sum S_i \left| V_i - \left(\frac{\sum V_i S_i}{\sum S_i}\right)\right|\right)}{\sum (V_i S_i)}\right]\right\} \qquad \text{...[9]}$$

where S_i is the distance (m) from the pivot to the i^{th} equally spaced catch container and V_i is the volume of the catch in the i^{th} container (mm or ml).

Low-Quarter Distribution Uniformity

The distribution uniformity represents the spatial evenness of the applied water across a field or a farm, as well as within a field or farm. The general form of the distribution uniformity can be given as

$$D_{Up} = 100\left(\frac{\overline{V_p}}{\overline{V_f}}\right) \qquad \text{...[10]}$$

where D_{Up} is the distribution uniformity in percent for the lowest "p" fraction of the field or farm (lowest one-half p = ½, lowest one-quarter p = ¼), $\overline{V_p}$ is the mean application volume (m^3), and $\overline{V_f}$ is the mean application volume (m^3) for the whole field or farm. When p = ½ and C_U > 70%, then the D_U and C_U are essentially equal (Warrick, 1983). The USDA-NRCS (formerly, the Soil Conservation Service) has widely used D_{Ulq} (p = ¼) for surface irrigation to assess the uniformity applied to a field, i.e., by the irrigation volume (amount) received by the lowest one-quarter of the field from applications for the whole field. Typically, D_{Up} is based on the post-irrigation measurement (Burt et al., 1997) of water volume that infiltrates the soil because it can more easily be measured and better represents the water available to the crop. However, the post-irrigation infiltrated water ignores any water intercepted by the crop and evaporated and any soil water evaporation that occurs before the measurement. Any water that percolates beneath the root zone or the sampling depth will also be ignored.

The D_U and C_U coefficients are mathematically interrelated through the statistical variation (coefficient of variation, $\sigma/\overline{x}$, C_v) and the type of distribution. Warrick (1983) presented relationships between D_U and C_U for normal, log normal, uniform, specialized power, beta, and gamma distributions of applied irrigations.

Emission Uniformity

For microirrigation systems, both the C_U and D_U concepts are impractical because the entire soil surface is not wetted. Keller and Karmeli (1975) developed an equation for microirrigation design as follows:

$$E_U = 100\left[1 - 1.27\,(C_{vm})\; n^{-1/2}\right]\left(\frac{q_m}{\bar{q}}\right) \qquad \text{...[11]}$$

where E_U is the design emission uniformity in percent, C_{vm} is the manufacturer's coefficient of variability in emission device flow rate (l/h), n is the number of emitters per plant, q_m is the minimum emission device flow rate (l/h) at the minimum system pressure, and $\bar{q}$ is the mean emission device flow rate (l/h). This equation is based on the D_{Ulq} concept (Heermann et al., 1990), and includes the influence of multiple emitters per plant that each may have a flow rate from a population of random flow rates based on the emission device manufacturing variation. Nakayama et al. (1979) developed a design coefficient based more closely to the C_U concept for emission device flow rates from a normal distribution given as

$$C_{Ud} = 100\left(1 - 0.798\,(C_{vm})\; n^{-1/2}\right) \qquad \text{...[12]}$$

where C_{Ud} is the coefficient of design uniformity in percent and the numerical value, 0.798, is $(2/\pi)^{0.5}$ from equation [8].

Many additional factors affect microirrigation uniformity including hydraulic factors, topographic factors, and emitter plugging or clogging.

WATER USE EFFICIENCY

The previous sections discussed the engineering aspects of irrigation efficiency. Irrigation efficiency clearly is influenced by the amount of water used in relation to the irrigation water applied to the crop and the uniformity of the applied water. These efficiency factors impact irrigation costs, irrigation design, and more importantly, in some cases, the crop productivity. The water use efficiency has been the most widely used parameter to describe irrigation effectiveness in terms of crop yield. Viets (1962) defined water use efficiency as

$$WUE = \frac{Y_g}{ET} \qquad \text{...[13]}$$

where WUE is water use efficiency (kg m^{-3}), Y_g is the economic yield (g m^{-2}), and ET is the crop water use (mm). WUE is usually expressed by the economic yield, but it has been historically expressed as well in terms of the crop dry matter yield (either total biomass or above-ground dry matter). These two WUE bases (economic yield or dry matter yield) have led to some inconsistencies in the use of the WUE concept. The transpiration ratio (transpiration per unit dry matter) is a more consistent value that depends primarily on crop species and the environmental evaporative demand (Tanner and Sinclair, 1983), and it is simply the inverse of WUE expressed on a dry matter basis. Howell (2001) discussed means to enhance WUE in irrigated agriculture including

- agronomic
- engineering
- management
- institutional

aspects that need to be considered. In the future, WUE will become as important as irrigation efficiency as the need for greater productivity from our natural resources develops with our increasing population and urbanization.

Irrigation Water Use Efficiency

The previous discussion of WUE doesn't explicitly explain the crop yield response to just irrigation. WUE is influenced by the crop water use (ET), but ET often includes a n important component from stored soil water and rainfall. Bos (1979) defined a term for water use efficiency to characterize the influence of irrigation on WUE as

$$WUE = \frac{(Y_{gi} - Y_{gd})}{(ET_i - ET_d)} \qquad \text{...[14]}$$

where WUE is irrigation water use efficiency (kg m^{-3}), Y_{gi} is the economic yield (g m^{-2}) for irrigation level i, Y_{gd} is the dryland yield (g m^{-2}) (actually, the crop yield without irrigation), ET_i is the evapotranspiration (mm) for irrigation level i, and ET_d is the evapotranspiration of the dryland crops (or of the ET without irrigation). Although equation [14] seems easy to use, both Y_{gd} and ET_d are difficult to evaluate. If the purpose is to compare irrigation and dryland production systems, then dryland rather than non-irrigated conditions should be used. If the purpose is to compare irrigated regimes with an unirrigated regime, then appropriate values for Y_{gd} and ET_d should be used. Often, in most semi-arid to arid locations, Y_{gd} may be zero. Eq. [14] differs principally from Eq. [13] by the yield from rainfed or dryland crop and the influence of rain and stored soil water in these systems that affect ET_d.

Bos (1979) defined irrigation water use efficiency as

$$IWUE = \frac{(Y_{gi} - Y_{gd})}{IRR_i} \qquad \ldots[15]$$

where IWUE is the irrigation efficiency (kg m^{-3}) and IRR_i is the irrigation water applied (mm) for irrigation level i. In Eq. [15], Y_{gd} may be often be zero in many arid situations.

For well-managed systems, typically WUE will be maximized near full ET while IWUE will be maximized at an irrigation level below full ET (Howell, 2001). Few examples have been documented over larger spatial scales, but it is apparent that WUE and IWUE can be improved further. In addition, WUE under good irrigation management with efficient irrigation systems almost always is better than WUE from rainfed or dryland systems due to the water offset required to produce enough biomass to create an economic yield.

SUMMARY

Irrigation efficiency is an important engineering term that involves understanding soil and agronomic sciences to achieve the greatest benefit from irrigation. The enhanced understanding of irrigation efficiency can improve the beneficial use of limited and declining water resources needed to enhance crop and food production from irrigated lands. Irrigation efficiency and irrigation uniformity measures should be used to assess field or design performance (Merriam and Keller, 1978; Pitts et al., 1996) to improve irrigation systems. Pitts et al. (1996) documented in California for 385 systems that were evaluated, improvements were recommended in 80% of the systems. In the systems that adopted recommended improvements, the DU_{lq} was improved by 18% in DU_{lq}.

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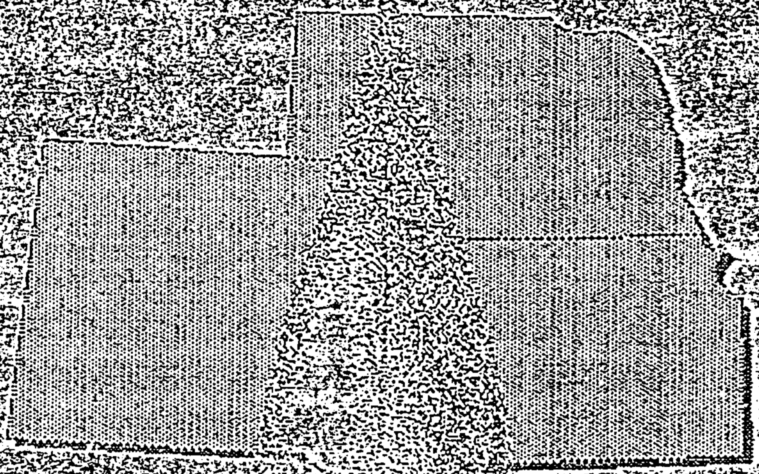

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